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IR Emission from AGNs

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Abstract

Unified schemes of active galactic nuclei (AGN) require an obscuring dusty torus around the central engine. Torus sizes of hundreds of parsecs were deduced from early theoretical modeling efforts, but high-resolution IR observations now show that the torus size is no more than a few parsecs. This conflict is resolved when the clumpy nature of the torus is taken into account. The compact torus may be best understood when identified with the dusty, optically thick region of the wind coming off the central accretion disk.

Key words:
Active galactic nuclei, quasars, Seyfert galaxies, dusty torus, disk winds

1 Introduction

The great diversity of AGN classes has been explained by a single unified scheme (e.g. Antonucci 1993; Urry & Padovani 1995). The nuclear activity is powered by a supermassive ($\sim 10^6$–10^{10} $M_\odot$) black hole and its accretion disk. This central engine is surrounded by dusty clouds, which are individually optically thick, in a toroidal structure (Krolik & Begelman 1988). Much of the observed diversity is simply the result of viewing this axisymmetric geometry from different angles. The clumpy torus provides anisotropic obscuration of the central region so that sources viewed face-on are recognized as type 1 objects, those observed edge-on are type 2. The fraction of the sky obscured by the torus determines the relative numbers of type 1 and 2 sources. From the statistics of Seyfert galaxies, Schmitt et al (2001) find that the torus height and radius obey $H/R \sim 1$. In the ubiquitous sketch by Urry & Padovani (1995),

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the torus is depicted as a large doughnut-like object, presumably populated by molecular clouds accreted from the galaxy. Gravity controls the orbital motions of the clouds, but the origin of cloud vertical motions capable of sustaining the "doughnut" in a steady-state with $H \sim R$ was recognized as a problem by Krolik & Begelman (1988). This problem has eluded solution to this date.

2 The Torus Size

Obscuration does not depend individually on either H or R, only on their ratio. To determine an actual size one must rely on the torus emission. In the absence of high-resolution IR observations, early estimates of the torus size came from theoretical analysis of the spectral energy distribution (SED). Pier & Krolik (1992) preformed the first detailed calculations of dust radiative transfer in a toroidal geometry. Because of the difficulties in modeling a clumpy medium, Pier & Krolik approximated the density distribution with a uniform one instead. They concluded that the torus has an outer radius $R \sim$ 5–10 pc, but later speculated that this compact structure might be embedded in a much larger, and more diffuse, torus with $R \sim$ 30–100 pc (Pier & Krolik 1993). Granato and Danese (1994) extended the smooth-density calculations to more elaborate toroidal geometries. From comparisons of their model predictions with the observed IR emission at $\lambda \sim$ 10–25 μm they concluded that the torus must have an outer radius $R \gtrsim$ 300–1000 pc, and that its radial density profile must be constant; later, Granato et al (1997) settled on hundreds of pc as their estimate for the torus size. Subsequently, $R > 100$ pc became common lore.

The advent of high-resolution IR observations brought unambiguous evidence in support of Pier & Krolik's original proposal of compact torus dimensions. The best studied source is NGC1068. K-band imaging shows that the emission region has $R \lesssim 1$ pc (Weigelt et al 2004). VLTI interferometry shows that the 10 μm flux comes from a hot ($T > 800$ K) central region of ~ 1 pc and its cooler ($T \sim 320$ K) surrounding within $R \sim$ 2–3 pc (Jaffe et al 2004). Keck observations established that $R < 17$ pc at 8–25 μm (Bock et al 2000). Recent Gemini observations by Mason et al (2005) confirm that $R < 15$ pc at 12μm and show that mid-IR observations at larger apertures are dominated by extended, low-brightness dust emission from the ionization cones. Similarly compact dimensions are found in high-resolution IR observations of other AGN: Circinus — $R \sim 1$ pc at 2.2 μm (Prieto et al 2004) and $R \lesssim 2$ pc at 8.7 μm and 18 μm (Packham et al 2005); NGC4151 — Swain et al (2003) find marginally resolved 2.2 μm emission with $R \leq 0.05$ pc, and Radomski et al (2003) find $R < 17$ pc at 10 μm and 18 μm; NGC1097 — $R < 5$ pc in near IR (Prieto et al 2005).

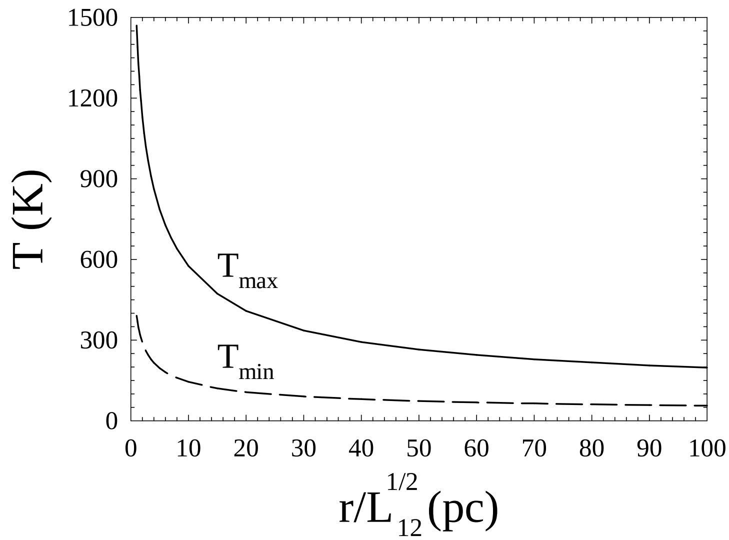

Fig. 1. The highest ($T_{\rm max}$) and lowest ($T_{\rm min}$) dust temperatures on the surface of an optically thick cloud at distance r from an AGN with luminosity $L_{12} = L/10^{12}L_{\odot}$. The highest temperature occurs on the illuminated face, the lowest on the dark side (from Nenkova et al 2005).

It can be argued that IR observations only determine the size of the corresponding emission region and that the actual torus size could in fact be much larger, but mid-IR flux considerations were the sole reason for introducing large sizes in the first place. In addition to IR, detailed studies of the central regions of active galaxies were made in CO observations. Schinnerer et al (2000) trace rotating molecular clouds in NGC1068 down to a distance of about 13 pc from the nucleus. From the velocity dispersions they find that at $R \simeq 70$ pc, the height of the molecular cloud distribution is only $H \sim$ 9–10 pc, for $H/R \sim 0.15$. Thus, although resembling the putative torus, the distribution of these clouds does not meet the unification scheme requirement $H/R \sim 1$; evidently, these clouds reside outside the torus, in accord with the IR observations.

In establishing compact torus sizes, IR observations have eliminated the only rationale for large dimensions and uncovered a fundamental discrepancy with the modeling results. Dust emission at 10 μm requires $T \sim$ 200–300 K, in turn implying large distances from the heating source. The constant radial density profiles and large dimensions deduced from the torus modeling merely reflected the large amounts of cool dust needed to produce the observed IR flux. Since dust temperature is uniquely related to distance from the AGN in smooth density distributions, it is impossible to get around this fundamental difficulty. However, in clumpy media the one-to-one correspondence between distance and temperature no longer holds. The temperature of an optically thick dusty cloud is much higher on the side illuminated by the AGN than on the dark side (Nenkova et al 2002). In contrast with smooth density distributions, in a

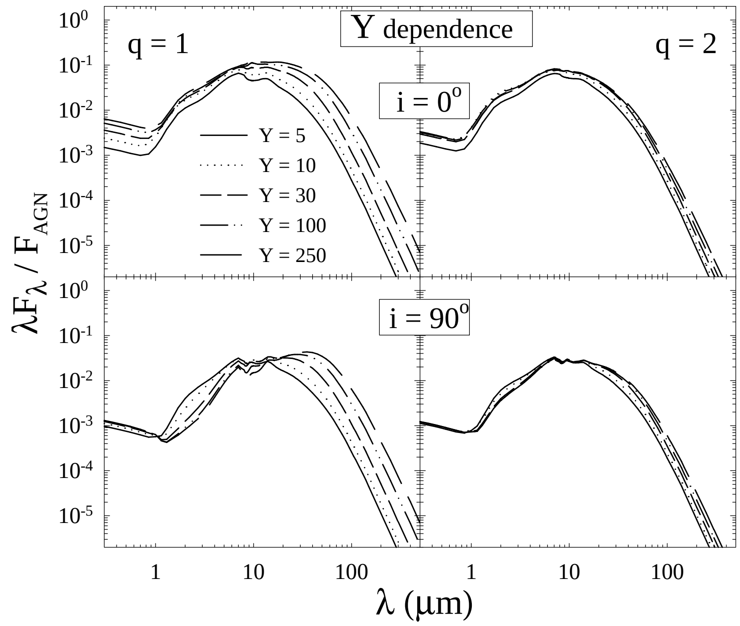

Fig. 2. Dependence of the SED on the torus radial thickness $Y = R/R_{\rm i}$, where the inner radius $R_{\rm i}$ is determined by dust sublimation at 1500 K. The torus is comprised of clouds, each with visual optical depth $\tau_{\rm V} = 60$, and has a total of 5 clouds, on average, along radial equatorial rays. The clouds radial distribution is $\propto 1/r^q$, with $q = 1$ and 2 as indicated, and their angular distribution is Gaussian with $\sigma = 45°$. Pole-on viewing is $i = 0°$, edge-on $i = 90°$. The torus size has a negligible effect in the case of the steeper power law $q = 2$ (from Nenkova et al 2005).

clumpy medium with cloud sizes much smaller than radial distances,

- Different dust temperatures coexist at the same distance from the AGN
- The same temperature occurs at different distances — the dark side of a cloud close to the AGN can be as warm as the bright side of a farther cloud

Figure 1 shows the distance variation of temperature on the bright and dark sides of an optically thick cloud. When the illuminated face is at $T = 900$ K, the dust temperature on the dark side is only $T \lesssim 300$ K. Therefore, even at the compact dimensions established by the observations, AGN tori contain cool dust thanks to their clumpy nature. Detailed modeling of IR emission from clumpy tori (Nenkova et al 2002, 2005) easily produce SED similar to those observed in AGN even for R as small as 5 pc. Figure 2 shows that varying the radial size of a clumpy torus by as much as a factor of 50 has only a small impact on its SED. The effect of overall size is confined mostly to long wavelengths when the radial cloud distribution varies as $1/r$, disappearing altogether for the steeper distribution $1/r^2$.

3 The Torus as a Disk Wind

Compact torus sizes give strong impetus for an alternative scenario to the steady-state "doughnut", involving cloud outflow in hydromagnetic disk winds. In this approach, which was advanced by numerous authors (Emmering et al 1992; Königl & Kartje 1994; Bottorff et al 1997, 2000; Kartje at al 1999), the proverbial torus is merely a particular region in the wind which happens to provide the toroidal obscuration required by unification schemes. The two scenarios differ fundamentally. In the first, clouds flowing in from the galaxy settle into closed-orbit motions around the center, their velocities containing comparable vertical and rotational components. The result is a puffed-up steady-state structure around the central engine — the "doughnut". It is a well-defined component of the system, separate from the accretion disk and any wind that might be coming off its surface. In contrast, in the torus-as-a-wind scenario the torus is simply that region of the clumpy wind wherein the clouds are dusty and optically thick. Cloud inflow from the galaxy does feed the central accretion disk, but it is not presumed to produce a separate puffed-up structure, which need not exist at all in this approach.

The disk-wind scenario does not suffer from the vertical-support problem of the "doughnut", but questions involving the cloud-uplift and wind-driving mechanisms are still unsettled. However, although the theoretical issues are not yet fully resolved, observations give ample evidence for winds and cloud motions in AGN (see, e.g., Elvis 2004), and even provide support for a disk-wind geometry (Hall et al 2003). In particular, recent H_2O maser observations in NGC3079 provide evidence for the uplift of molecular clouds off the disk surface and their subsequent outflow along rotating streamlines (Kondratko et al 2005). We are currently attempting to incorporate in the disk wind scenario the observational constraints on the clumpy obscuration (Elitzur & Shlosman, in preparation). If successful, the outcome will be a "grand unification scheme" in which the clouds responsible for disparate phenomena such as broad emission and absorption lines, warm absorption, and the toroidal obscuration are all members of a single clumpy disk wind, distinguished from each other only by their physical properties which are controlled by location in the outflow.

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